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Balakin

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(54) SEMI-VERTICAL POSITIONING METHOD AND APPARATUS USED IN CONJUNCTION WITH A CHARGED PARTICLE CANCER THERAPY SYSTEM

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(58) **Field of Classification Search**

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See application file for complete search history.

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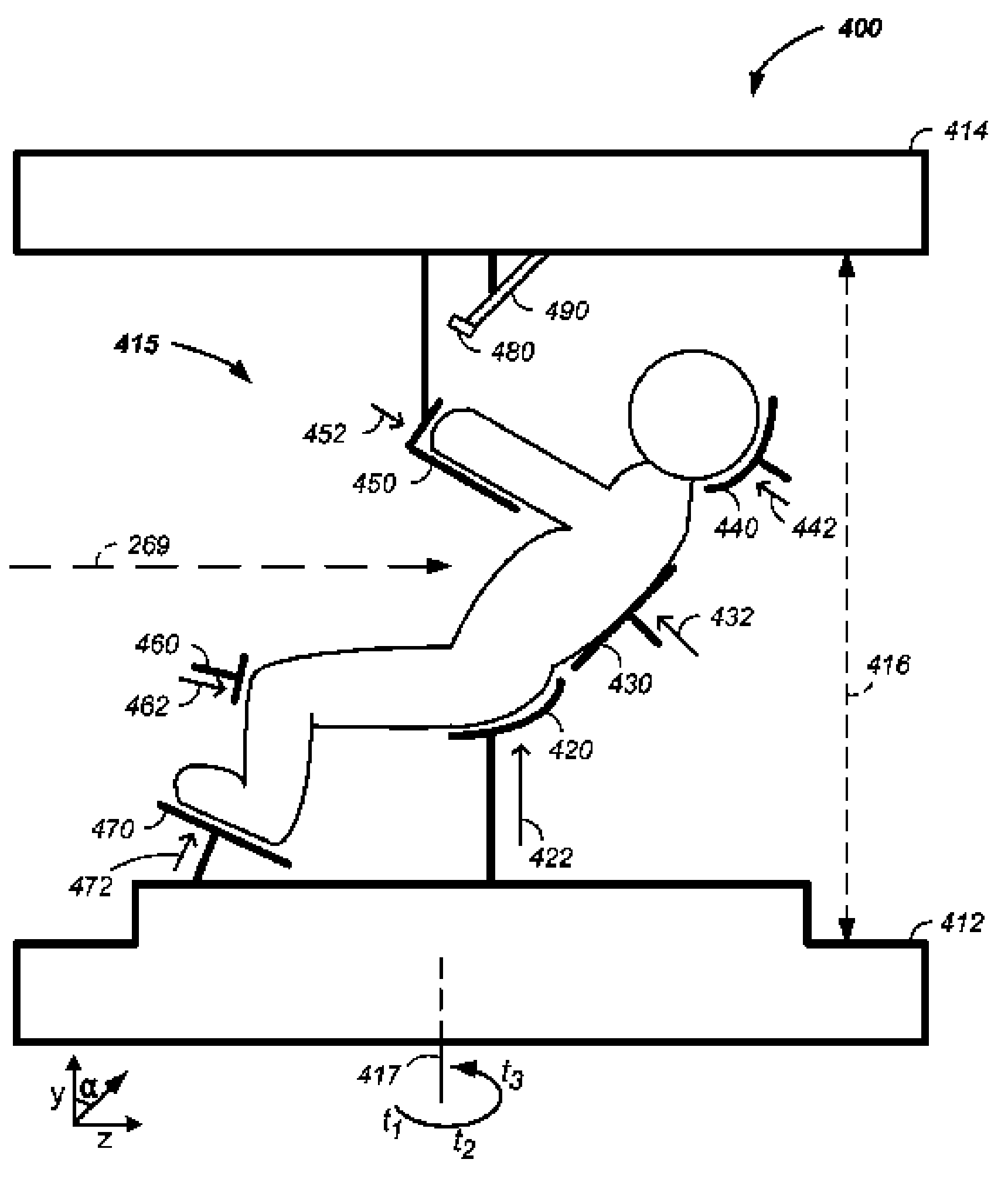
(57) ABSTRACT

The invention comprises a semi-vertical patient positioning, alignment, and/or control method and apparatus used in conjunction with charged particle or proton beam radiation therapy of cancerous tumors. Patient positioning constraints are used to maintain the patient in a treatment position, including one or more of: a seat support, a back support, a head support, an arm support, a knee support, and a foot support. One or more of the positioning constraints are movable and/or under computer control for rapid positioning and/or immobilization of the patient. The system optionally uses an X-ray beam that lies in substantially the same path as a proton beam path of a particle beam cancer therapy system. The generated image is usable for: fine tuning body alignment relative to the proton beam path, to control the proton beam path to accurately and precisely target the tumor, and/or in system verification and validation.

26 Claims, 6 Drawing Sheets



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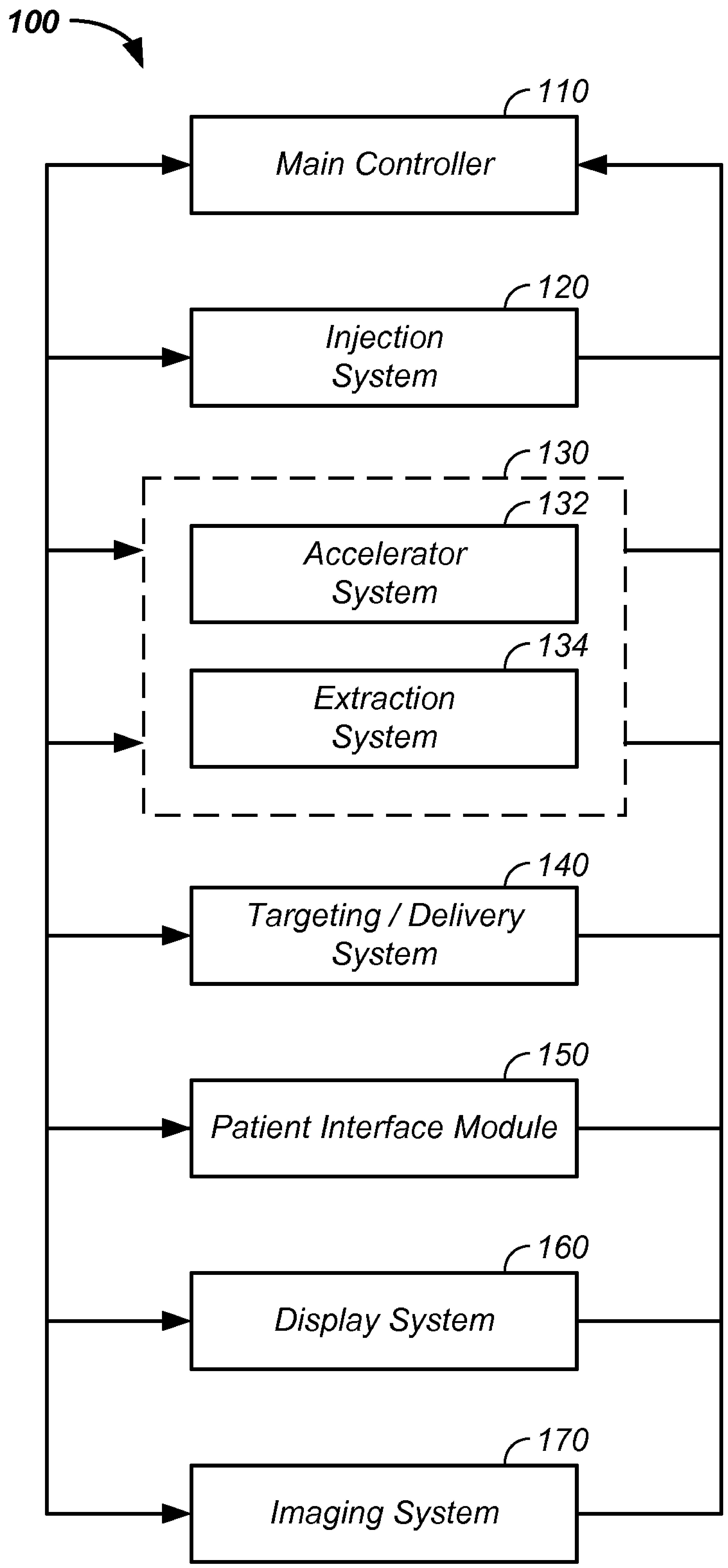
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132
Accelerator System
134
Extraction System
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Targeting / Delivery System
150
Patient Interface Module
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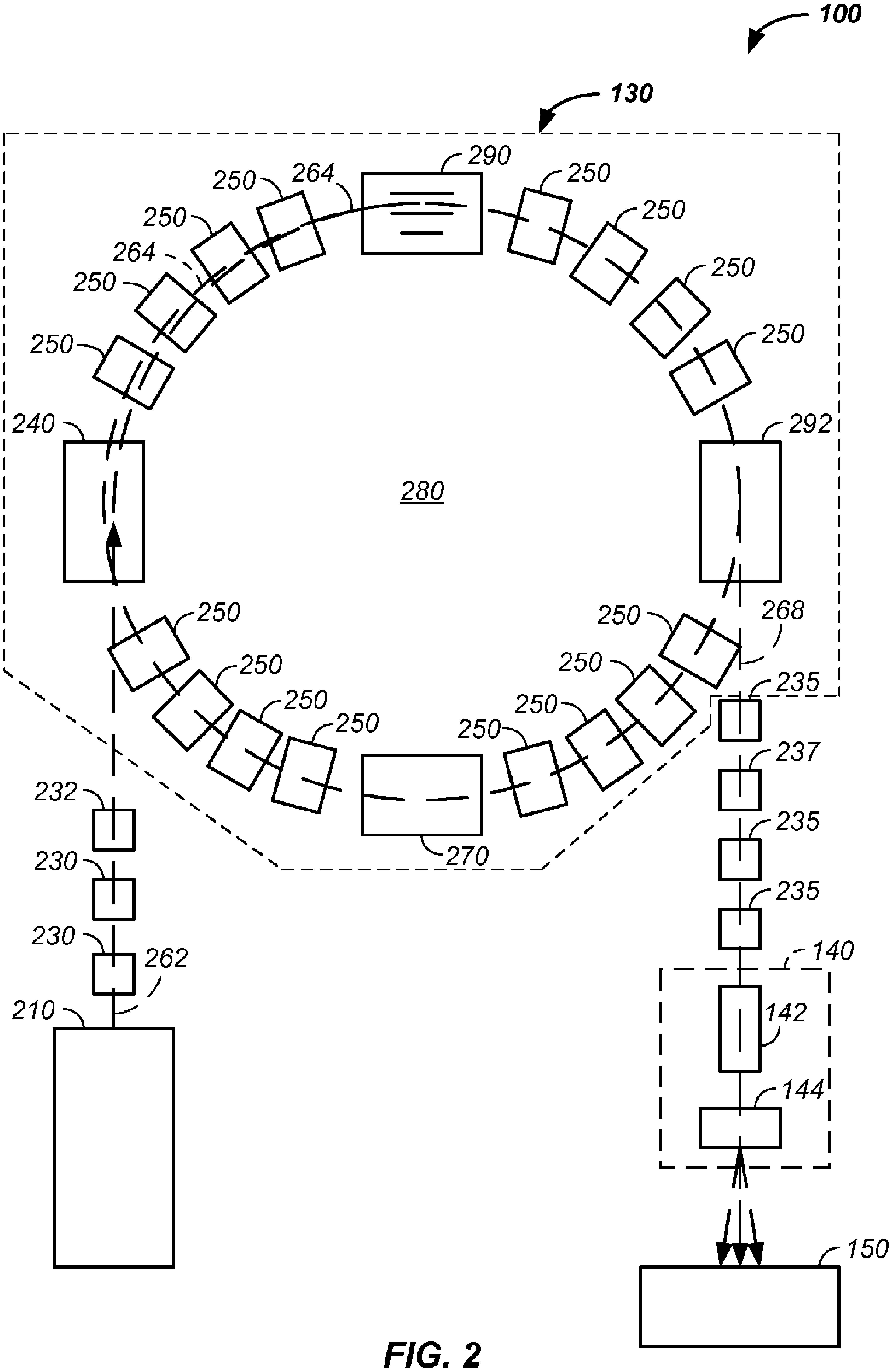
Display System
170
Imaging System

FIG. 1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144
150

FIG. 2

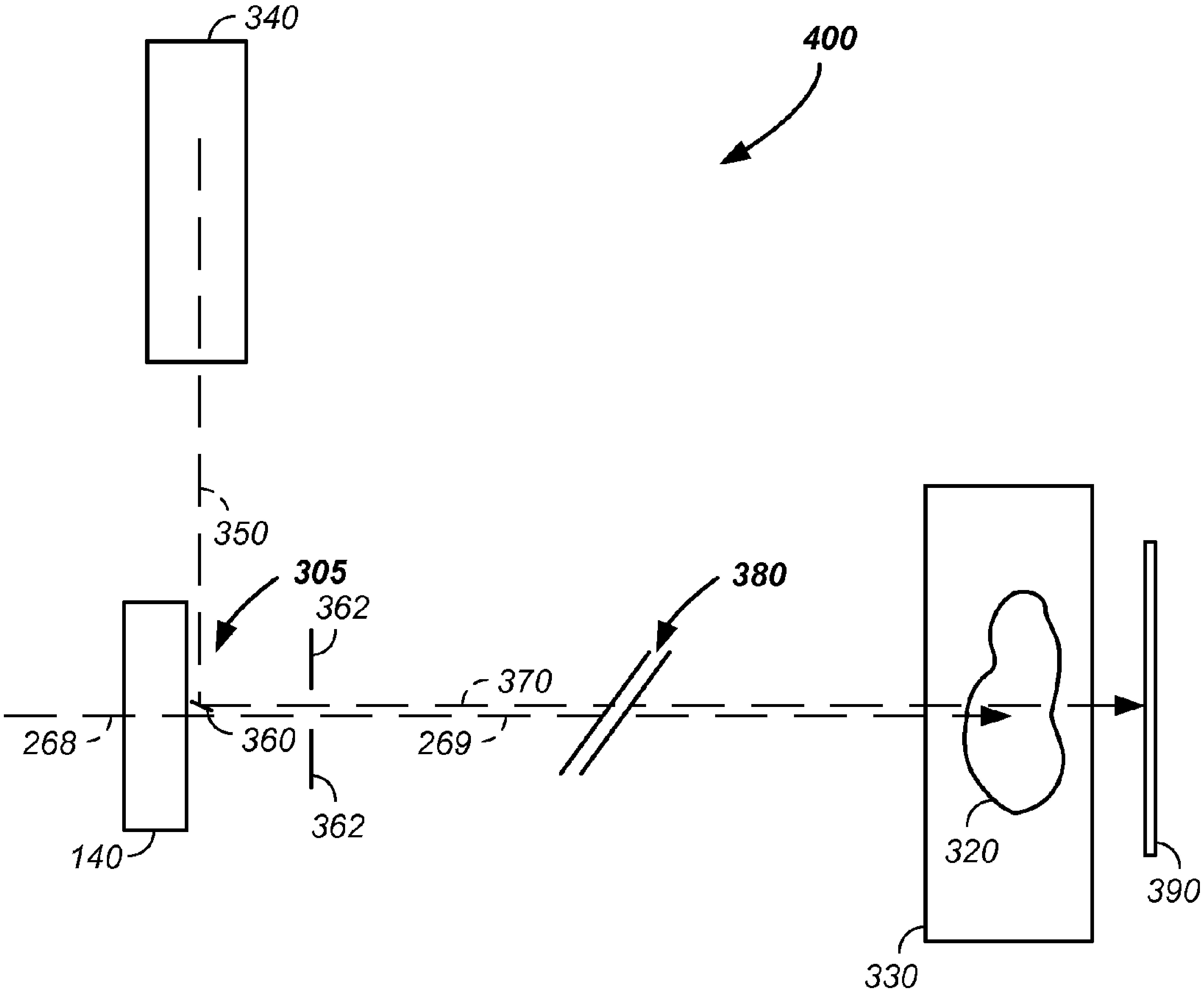
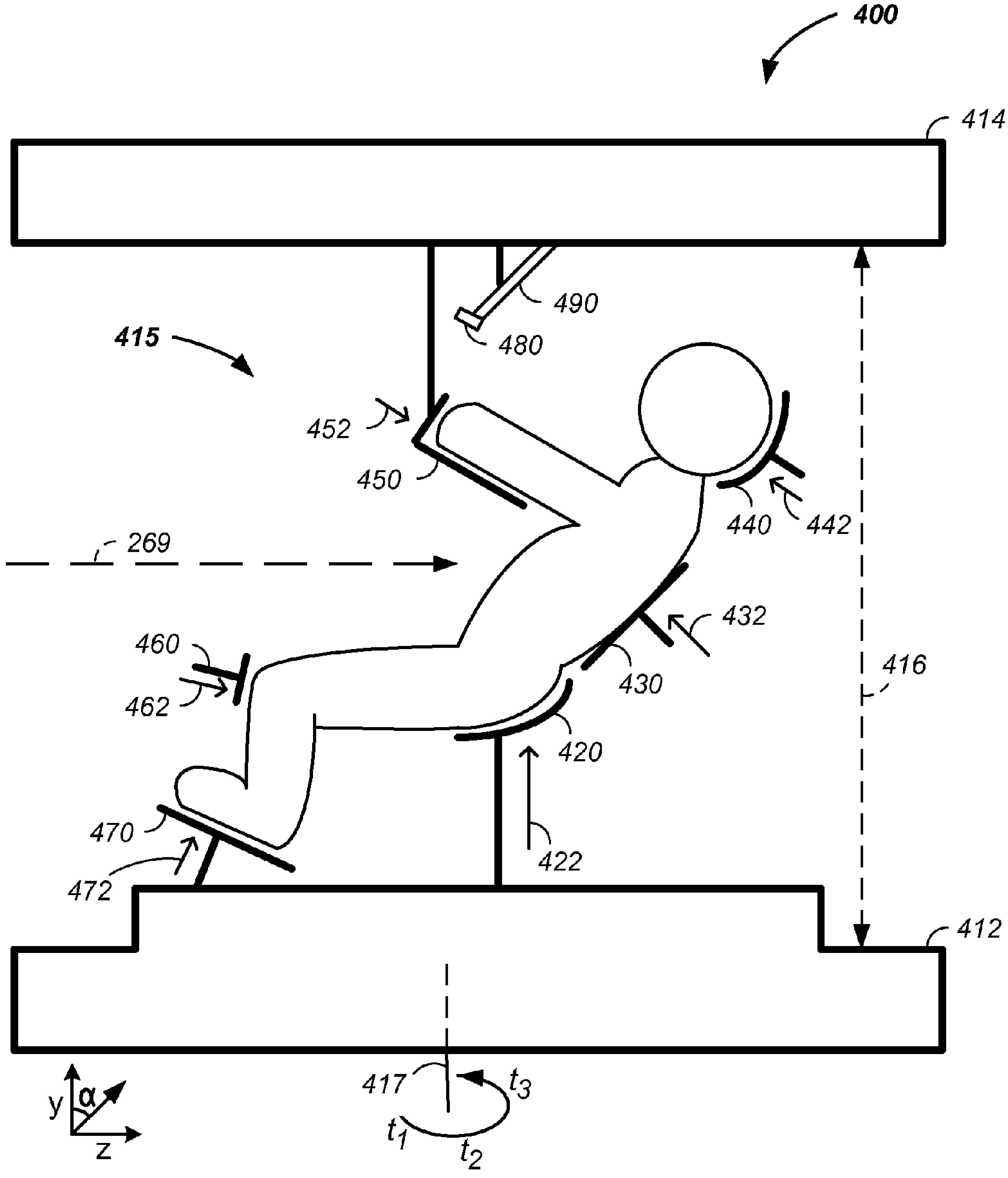


FIG. 3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y
α
z
417
t_3
t_1
t_2

FIG. 4

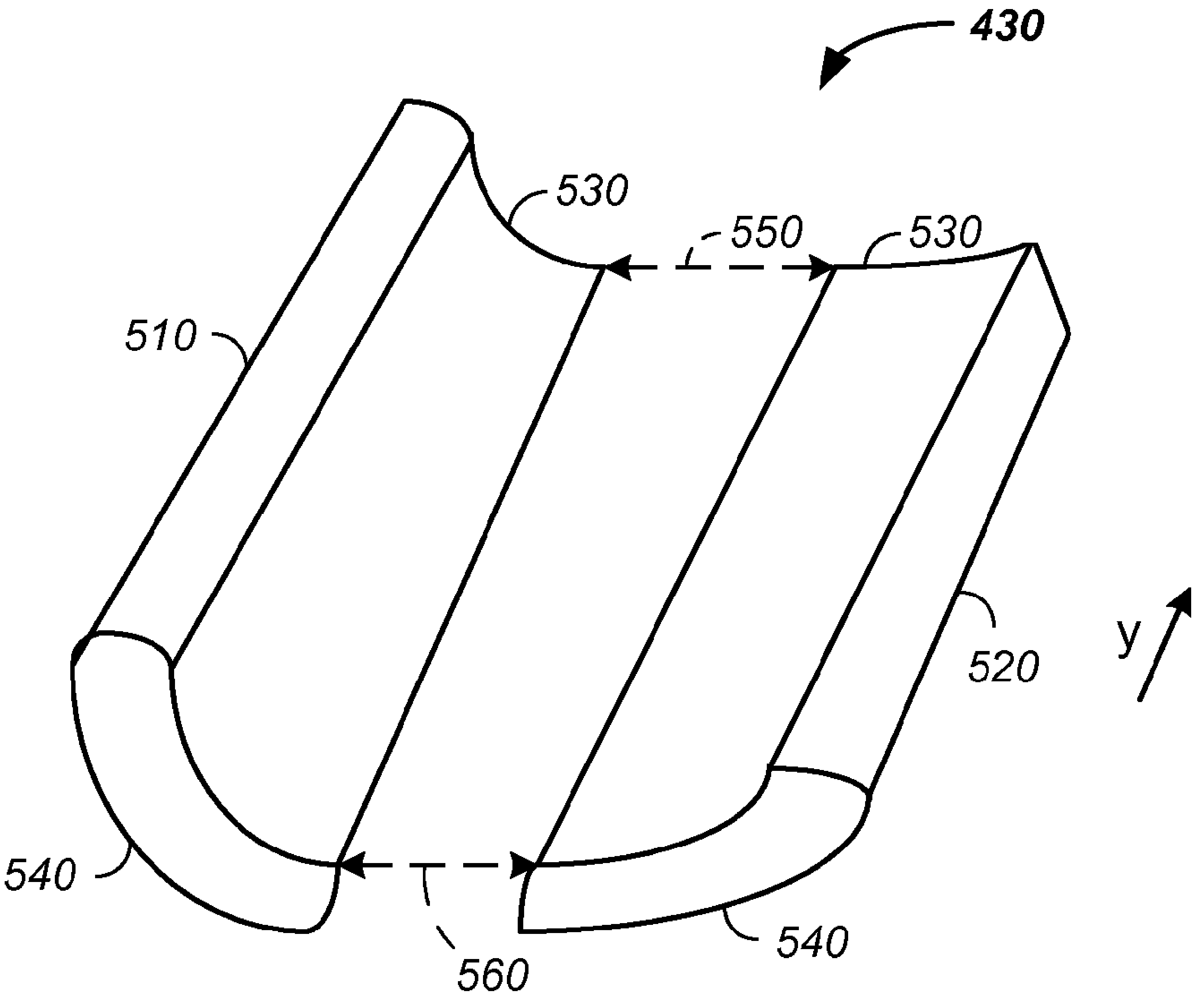

FIG. 5

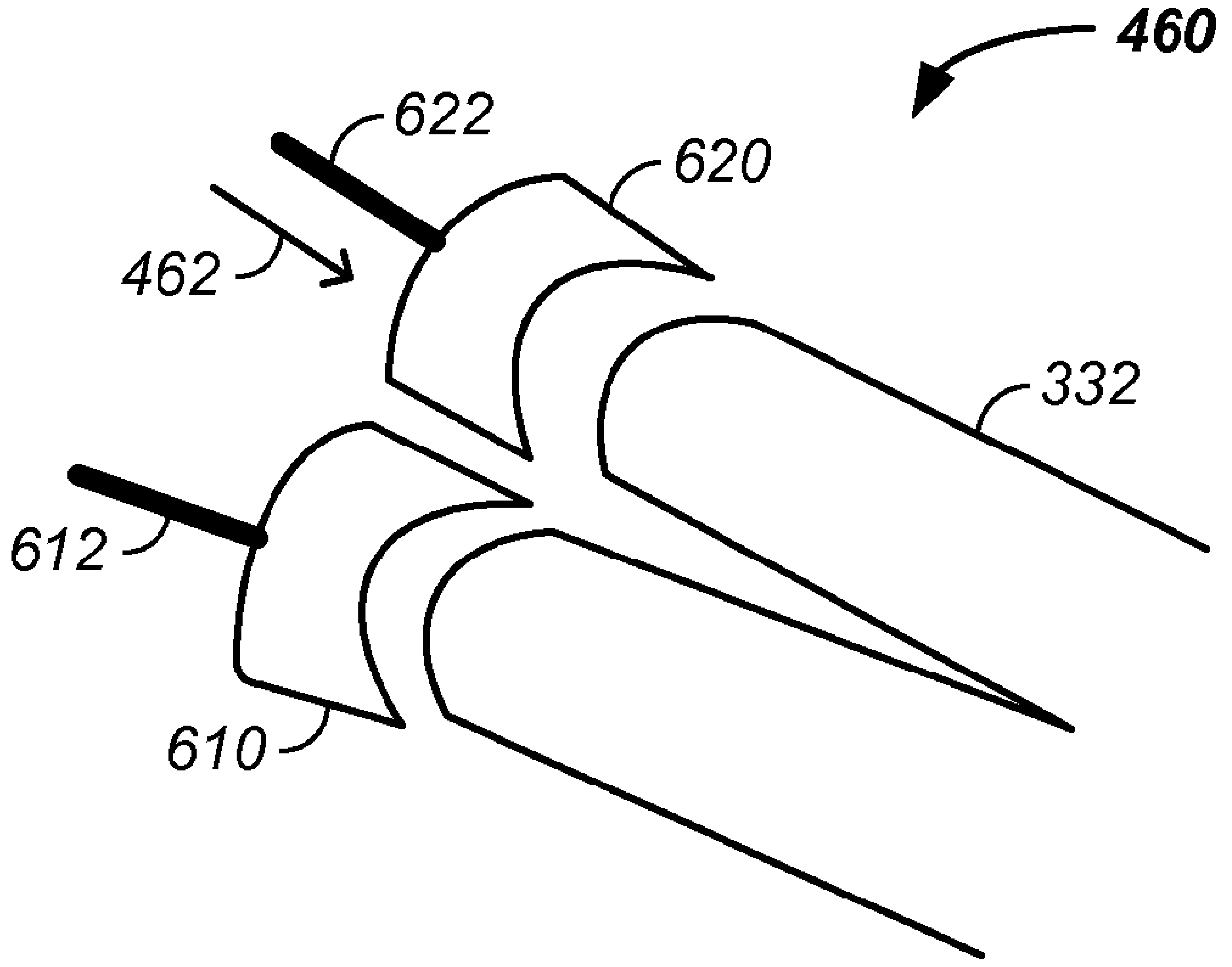

FIG. 6

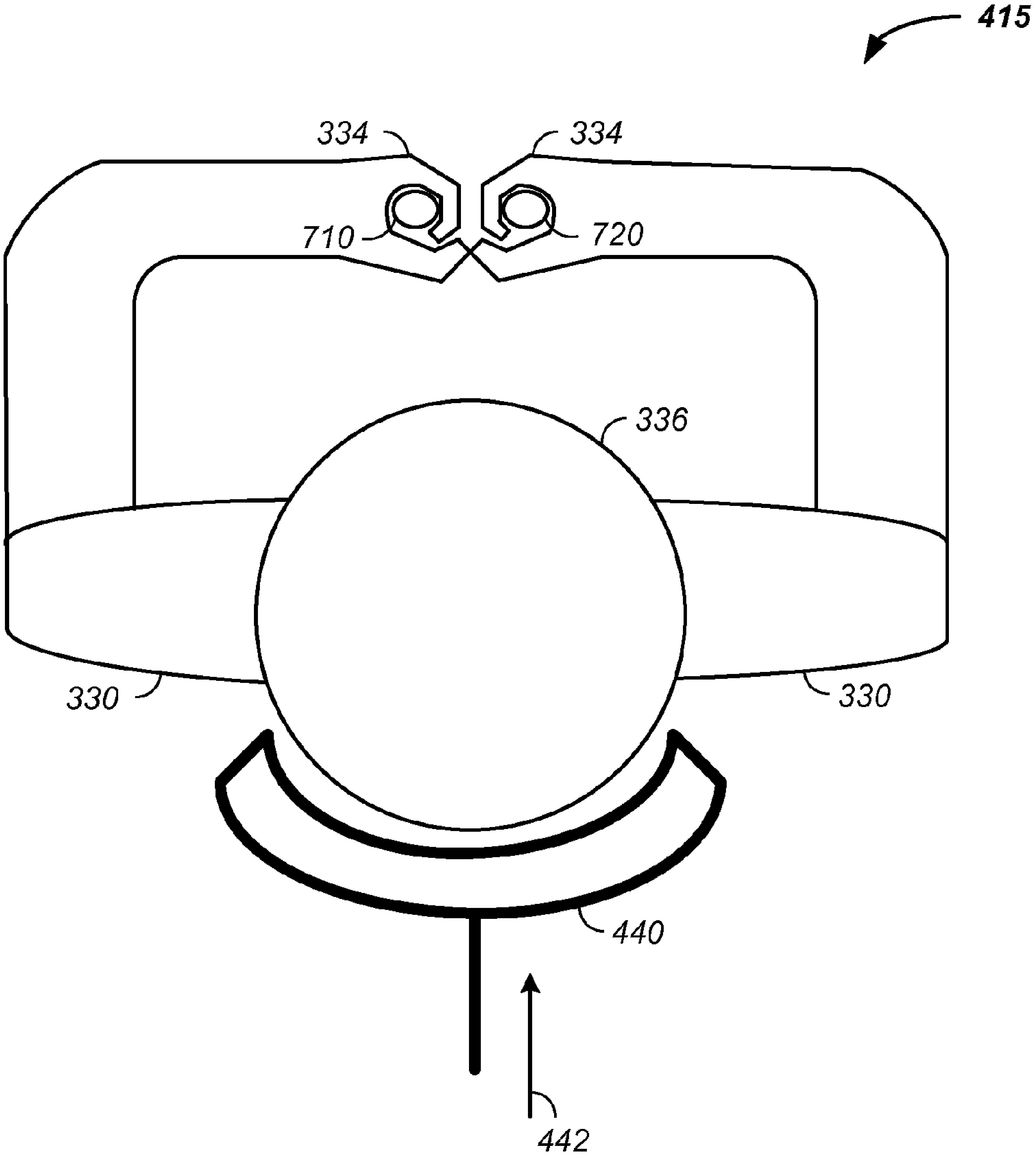

FIG. 7

SEMI-VERTICAL POSITIONING METHOD AND APPARATUS USED IN CONJUNCTION WITH A CHARGED PARTICLE CANCER THERAPY SYSTEM

CROSS REFERENCES TO RELATED APPLICATIONS

This application claims benefit of:

U.S. provisional patent application No. 61/055,395 filed May 22, 2008;

U.S. provisional patent application No. 61/137,574 filed Aug. 1, 2008;

U.S. provisional patent application No. 61/192,245 filed Sep. 17, 2008;

U.S. provisional patent application No. 61/055,409 filed May 22, 2008;

U.S. provisional patent application No. 61/203,308 filed Dec. 22, 2008;

U.S. provisional patent application No. 61/188,407 filed Aug. 11, 2008;

U.S. provisional patent application No. 61/209,529 filed Mar. 9, 2009;

U.S. provisional patent application No. 61/188,406 filed Aug. 11, 2008;

U.S. provisional patent application No. 61/189,815 filed Aug. 25, 2008;

U.S. provisional patent application No. 61/208,182 filed Feb. 23, 2009;

U.S. provisional patent application No. 61/201,731 filed Dec. 15, 2008;

U.S. provisional patent application No. 61/208,971 filed Mar. 3, 2009;

U.S. provisional patent application No. 61/205,362 filed Jan. 21, 2009;

U.S. provisional patent application No. 61/134,717 filed Jul. 14, 2008;

U.S. provisional patent application No. 61/134,707 filed Jul. 14, 2008;

U.S. provisional patent application No. 61/201,732 filed Dec. 15, 2008;

U.S. provisional patent application No. 61/198,509 filed Nov. 7, 2008;

U.S. provisional patent application No. 61/134,718 filed Jul. 14, 2008;

U.S. provisional patent application No. 61/190,613 filed Sep. 2, 2008;

U.S. provisional patent application No. 61/191,043 filed Sep. 8, 2008;

U.S. provisional patent application No. 61/192,237 filed Sep. 17, 2008;

U.S. provisional patent application No. 61/201,728 filed Dec. 15, 2008;

U.S. provisional patent application No. 61/190,546 filed Sep. 2, 2008;

U.S. provisional patent application No. 61/189,017 filed Aug. 15, 2008;

U.S. provisional patent application No. 61/198,248 filed Nov. 5, 2008;

U.S. provisional patent application No. 61/198,508 filed Nov. 7, 2008;

U.S. provisional patent application No. 61/197,971 filed Nov. 3, 2008;

U.S. provisional patent application No. 61/199,405 filed Nov. 17, 2008;

U.S. provisional patent application No. 61/199,403 filed Nov. 17, 2008; and

U.S. provisional patent application No. 61/199,404 filed Nov. 17, 2008,

all of which are incorporated herein in their entirety by this reference thereto.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to treatment of solid cancers. More particularly, the invention relates to a method and apparatus used in conjunction with radiation treatment of cancerous tumors.

2. Discussion of the Prior Art

Cancer

A tumor is an abnormal mass of tissue. Tumors are either benign or malignant. A benign tumor grows locally, but does not spread to other parts of the body. Benign tumors cause problems because of their spread, as they press and displace normal tissues. Benign tumors are dangerous in confined places such as the skull. A malignant tumor is capable of invading other regions of the body. Metastasis is cancer spreading by invading normal tissue and spreading to distant tissues.

Cancer Treatment

Several forms of radiation therapy exist for cancer treatment including: brachytherapy, traditional electromagnetic X-ray therapy, and proton therapy. Each are further described, infra.

Brachytherapy is radiation therapy using radioactive sources implanted inside the body. In this treatment, an oncologist implants radioactive material directly into the tumor or very close to it. Radioactive sources are also placed within body cavities, such as the uterine cervix.

The second form of traditional cancer treatment using electromagnetic radiation includes treatment using X-rays and gamma rays. An X-ray is high-energy, ionizing, electromagnetic radiation that is used at low doses to diagnose disease or at high doses to treat cancer. An X-ray or Röntgen ray is a form of electromagnetic radiation with a wavelength in the range of 10 to 0.01 nanometers (nm), corresponding to frequencies in the range of 30 PHz to 30 EHz. X-rays are longer than gamma rays and shorter than ultraviolet rays. X-rays are primarily used for diagnostic radiography. X-rays are a form of ionizing radiation and as such can be dangerous. Gamma rays are also a form of electromagnetic radiation and are at frequencies produced by sub-atomic particle interactions, such as electron-positron annihilation or radioactive decay. In the electromagnetic spectrum, gamma rays are generally characterized as electromagnetic radiation having the highest frequency, as having highest energy, and having the shortest wavelength, such as below about 10 picometers. Gamma rays consist of high energy photons with energies above about 100 keV. X-rays are commonly used to treat cancerous tumors. However, X-rays are not optimal for treatment of cancerous tissue as X-rays deposit their highest does of radiation near the surface of the targeted tissue and delivery exponentially less radiation as they penetrate into the tissue. This results in large amounts of radiation being delivered outside of the tumor. Gamma rays have similar limitations.

The third form of cancer treatment uses protons. Proton therapy systems typically include: a beam generator, an accelerator, and a beam transport system to move the resulting accelerated protons to a plurality of treatment rooms where the protons are delivered to a tumor in a patient's body.

Proton therapy works by aiming energetic ionizing particles, such as protons accelerated with a particle accelerator, onto a target tumor. These particles damage the DNA of cells, ultimately causing their death. Cancerous cells, because of their high rate of division and their reduced ability to repair damaged DNA, are particularly vulnerable to attack on their DNA.

Due to their relatively enormous size, protons scatter less easily in the tissue and there is very little lateral dispersion. Hence, the proton beam stays focused on the tumor shape without much lateral damage to surrounding tissue. All protons of a given energy have a certain range, defined by the Bragg peak, and the dosage delivery to tissue ratio is maximum over just the last few millimeters of the particle's range. The penetration depth depends on the energy of the particles, which is directly related to the speed to which the particles were accelerated by the proton accelerator. The speed of the proton is adjustable to the maximum rating of the accelerator. It is therefore possible to focus the cell damage due to the proton beam at the very depth in the tissues where the tumor is situated. Tissues situated before the Bragg peak receive some reduced dose and tissues situated after the peak receive none.

Synchrotrons

Patents related to the current invention are summarized here.

Proton Beam Therapy System

F. Cole, et. al. of Loma Linda University Medical Center "Multi-Station Proton Beam Therapy System", U.S. Pat. No. 4,870,287 (Sep. 26, 1989) describe a proton beam therapy system for selectively generating and transporting proton beams from a single proton source and accelerator to a selected treatment room of a plurality of patient treatment rooms.

Transport/Scanning Control

K. Matsuda, et. al. "Particle Beam Irradiation Apparatus, Treatment Planning Unit, and Particle Beam Irradiation Method", U.S. Pat. No. 7,227,161 (Jun. 5, 2007); K. Matsuda, et. al. "Particle Beam Irradiation Treatment Planning Unit, and Particle Beam Irradiation Method", U.S. Pat. No. 7,122, 8110 (Oct. 17, 2006); and K. Matsuda, et. al. "Particle Beam Irradiation Apparatus, Treatment Planning Unit, and Particle Beam Irradiation Method" (Sep. 5, 2006) describe a particle beam irradiation apparatus have a scanning controller that stops output of an ion beam, changes irradiation position via control of scanning electromagnets, and reinitiates treatment based on treatment planning information.

T. Norimine, et. al. "Particle Therapy System Apparatus", U.S. Pat. No. 7,060,997 (Jun. 13, 2006); T. Norimine, et. al. "Particle Therapy System Apparatus", U.S. Pat. No. 6,936, 832 (Aug. 30, 2005); and T. Norimine, et. al. "Particle Therapy System Apparatus", U.S. Pat. No. 6,774,383 (Aug. 10, 2004) each describe a particle therapy system having a first steering magnet and a second steering magnet disposed in a charged particle beam path after a synchrotron that are controlled by first and second beam position monitors.

K. Moriyama, et. al. "Particle Beam Therapy System", U.S. Pat. No. 7,012,267 (Mar. 14, 2006) describe a manual input to a ready signal indicating preparations are completed for transport of the ion beam to a patient.

H. Harada, et. al. "Irradiation Apparatus and Irradiation Method", U.S. Pat. No. 6,984,835 (Jan. 10, 2006) describe an irradiation method having a large irradiation filed capable of uniform dose distribution, without strengthening performance of an irradiation field device, using a position controller having overlapping area formed by a plurality of irradiations using a multileaf collimator. The system provides flat and uniform dose distribution over an entire surface of a target.

H. Akiyama, et. al. "Charged Particle Beam Irradiation Equipment Having Scanning Electromagnet Power Supplies", U.S. Pat. No. 6,903,351 (Jun. 7, 2005); H. Akiyama, et. al. "Charged Particle Beam Irradiation Equipment Having Scanning Electromagnet Power Supplies", U.S. Pat. No. 6,900,436 (May 31, 2005); and H. Akiyama, et. al. "Charged Particle Beam Irradiation Equipment Having Scanning Electromagnet Power Supplies", U.S. Pat. No. 6,881,970 (Apr. 19, 2005) all describe a power supply for applying a voltage to a scanning electromagnet for deflecting a charged particle beam and a second power supply without a pulsating component to control the scanning electromagnet more precisely allowing for uniform irradiation of the irradiation object.

K. Amemiya, et. al. "Accelerator System and Medical Accelerator Facility", U.S. Pat. No. 6,800,866 (Oct. 5, 2004) describe an accelerator system having a wide ion beam control current range capable of operating with low power consumption and having a long maintenance interval.

A. Dolinskii, et. al. "Gantry with an Ion-Optical System", U.S. Pat. No. 6,476,403 (Nov. 5, 2002) describe a gantry for an ion-optical system comprising an ion source and three bending magnets for deflecting an ion beam about an axis of rotation. A plurality of quadrupoles are also provided along the beam path to create a fully achromatic beam transport and an ion beam with difference emittances in the horizontal and vertical planes. Further, two scanning magnets are provided between the second and third bending magnets to direct the beam.

H. Akiyama, et. al. "Charged Particle Beam Irradiation Apparatus", U.S. Pat. No. 6,218,675 (Apr. 17, 2001) describe a charged particle beam irradiation apparatus for irradiating a target with a charged particle beam that include a plurality of scanning electromagnets and a quadrupole electromagnet between two of the plurality of scanning electromagnets.

K. Matsuda, et. al. "Charged Particle Beam Irradiation System and Method Thereof", U.S. Pat. No. 6,087,672 (Jul. 11, 2000) describe a charged particle beam irradiation system having a ridge filter with shielding elements to shield a part of the charged particle beam in an area corresponding to a thin region in said target.

P. Young, et. al. "Raster Scan Control System for a Charged-Particle Beam", U.S. Pat. No. 5,017,789 (May 21, 1991) describe a raster scan control system for use with a charged-particle beam delivery system that includes a nozzle through which a charged particle beam passes. The nozzle includes a programmable raster generator and both fast and slow sweep scan electromagnets that cooperate to generate a sweeping magnetic field that steers the beam along a desired raster scan pattern at a target.

Beam Shape Control

M. Yanagisawa, et. al. "Particle Beam Irradiation System and Method of Adjusting Irradiation Field Forming Apparatus", U.S. Pat. No. 7,154,107 (Dec. 26, 2006) and M. Yanagisawa, et. al. "Particle Beam Irradiation System and Method of Adjusting Irradiation Field Forming Apparatus", U.S. Pat. No. 7,049,613 (May 23, 2006) describe a particle therapy system having a scattering compensator and a range modulation wheel. Movement of the scattering compensator and the range modulation wheel adjusts a size of the ion beam and scattering intensity resulting in penumbra control and a more uniform dose distribution to a diseased body part.

T. Haberer, et. al. "Device and Method for Adapting the Size of an Ion Beam Spot in the Domain of Tumor Irradiation", U.S. Pat. No. 6,859,741 (Feb. 22, 2005) describe a method and apparatus for adapting the size of an ion beam in tumor irradiation. Quadrupole magnets determining the size of the ion beam spot are arranged directly in front of raster scanning magnets determining the size of the ion beam spot. The apparatus contains a control loop for obtaining current correction values to further control the ion beam spot size.

K. Matsuda, et. al. "Charged Particle Irradiation Apparatus and an Operating Method Thereof", U.S. Pat. No. 5,986,274 (Nov. 16, 1999) describe a charged particle irradiation apparatus capable of decreasing a lateral dose falloff at boundaries of an irradiation field of a charged particle beam using controlling magnet fields of quadrupole electromagnets and deflection electromagnets to control the center of the charged particle beam passing through the center of a scatterer irrespective of direction and intensity of a magnetic field generated by scanning electromagnets.

K. Hiramoto, et. al. "Charged Particle Beam Apparatus and Method for Operating the Same", U.S. Pat. No. 5,969,367 (Oct. 19, 1999) describe a charged particle beam apparatus where a the charged particle beam is enlarged by a scatterer resulting in a Gaussian distribution that allows overlapping of irradiation doses applied to varying spot positions.

M. Moyers, et. al. "Charged Particle Beam Scattering System", U.S. Pat. No. 5,440,133 (Aug. 8, 1995) describe a radiation treatment apparatus for producing a particle beam and a scattering foil for changing the diameter of the charged particle beam.

C. Nunan "Multileaf Collimator for Radiotherapy Machines", U.S. Pat. No. 4,868,844 (Sep. 19, 1989) describes a radiation therapy machine having a multileaf collimator formed of a plurality of heavy metal leaf bars movable to form a rectangular irradiation field.

R. Maughan, et. al. "Variable Radiation Collimator", U.S. Pat. No. 4,754,147 (Jun. 28, 1988) describe a variable collimator for shaping a cross-section of a radiation beam that relies on rods, which are positioned around a beam axis. The rods are shaped by a shaping member cut to a shape of an area of a patient go be irradiated.

Beam Energy/Intensity

M. Yanagisawa, et. al. "Charged Particle Therapy System, Range Modulation Wheel Device, and Method of Installing Range Modulation Wheel Device", U.S. Pat. No. 7,355,189 (Apr. 8, 2008) and Yanagisawa, et. al. "Charged Particle Therapy System, Range Modulation Wheel Device, and Method of Installing Range Modulation Wheel Device", U.S. Pat. No. 7,053,389 (May 30, 2008) both describe a particle therapy system having a range modulation wheel. The ion beam passes through the range modulation wheel resulting in a plurality of energy levels corresponding to a plurality of stepped thicknesses of the range modulation wheel.

M. Yanagisawa, et. al. "Particle Beam Irradiation System and Method of Adjusting Irradiation Apparatus", U.S. Pat. No. 7,297,967 (Nov. 20, 2007); M. Yanagisawa, et. al. "Particle Beam Irradiation System and Method of Adjusting Irradiation Apparatus", U.S. Pat. No. 7,071,479 (Jul. 4, 2006); M. Yanagisawa, et. al. "Particle Beam Irradiation System and Method of Adjusting Irradiation Apparatus", U.S. Pat. No. 7,026,636 (Apr. 11, 2006); and M. Yanagisawa, et. al. "Particle Beam Irradiation System and Method of Adjusting Irradiation Apparatus", U.S. Pat. No. 6,777,700 (Aug. 17, 2004) all describe a scattering device, a range adjustment device, and a peak spreading device. The scattering device and range adjustment device are combined together and are moved along a beam axis. The spreading device is independently moved along the axis to adjust the degree of ion beam scattering. Combined, the devise increases the degree of uniformity of radiation dose distribution to a diseased tissue.

A. Sliski, et. al. "Programmable Particle Scatterer for Radiation Therapy Beam Formation", U.S. Pat. No. 7,208,748 (Apr. 24, 2007) describe a programmable pathlength of a fluid disposed into a particle beam to modulate scattering angle and beam range in a predetermined manner. The charged particle beam scatterer/range modulator comprises a fluid reservoir having opposing walls in a particle beam path and a drive to adjust the distance between the walls of the fluid reservoir under control of a programmable controller to create a predetermined spread out Bragg peak at a predetermined depth in a tissue. The beam scattering and modulation is continuously and dynamically adjusted during treatment of a tumor to deposit a dose in a targeted predetermined three dimensional volume.

M. Tadokoro, et. al. "Particle Therapy System", U.S. Pat. No. 7,247,869 (Jul. 24, 2007) and U.S. Pat. No. 7,154,108 (Dec. 26, 2006) each describe a particle therapy system capable of measuring energy of a charged particle beam during irradiation during use. The system includes a beam passage between a pair of collimators, an energy detector mounted, and a signal processing unit.

G. Kraft, et. al. "Ion Beam Scanner System and Operating Method", U.S. Pat. No. 6,891,177 (May 10, 2005) describe an ion beam scanning system having a mechanical alignment system for the target volume to be scanned and allowing for depth modulation of the ion beam by means of a linear motor and transverse displacement of energy absorption means resulting in depth-staggered scanning of volume elements of a target volume.

G. Hartmann, et. al. "Method for Operating an Ion Beam Therapy System by Monitoring the Distribution of the Radiation Dose", U.S. Pat. No. 6,736,831 (May 18, 2004) describe a method for operation of an ion beam therapy system having a grid scanner and irradiates and scans an area surrounding an isocentre. Both the depth dose distribution and the transverse dose distribution of the grid scanner device at various positions in the region of the isocentre are measured and evaluated.

Y. Jongen "Method for Treating a Target Volume with a Particle Beam and Device Implementing Same", U.S. Pat. No. 6,717,162 (Apr. 6, 2004) describes a method of producing from a particle beam a narrow spot directed towards a target volume, characterized in that the spot sweeping speed and particle beam intensity are simultaneously varied.

G. Kraft, et. al. "Device for Irradiating a Tumor Tissue", U.S. Pat. No. 6,710,362 (Mar. 23, 2004) describe a method and apparatus of irradiating a tumor tissue, where the apparatus has an electromagnetically driven ion-braking device in the proton beam path for depth-wise adaptation of the proton beam that adjusts both the ion beam direction and ion beam range.

K. Matsuda, et. al. "Charged Particle Beam Irradiation Apparatus", U.S. Pat. No. 6,617,598 (Sep. 9, 2003) describe a charged particle beam irradiation apparatus that increased the width in a depth direction of a Bragg peak by passing the Bragg peak through an enlarging device containing three ion beam components having different energies produced according to the difference between passed positions of each of the filter elements.

H. Stelzer, et. al. "Ionization Chamber for Ion Beams and Method for Monitoring the Intensity of an Ion Beam", U.S. Pat. No. 6,437,513 (Aug. 20, 2002) describe an ionization chamber for ion beams and a method of monitoring the intensity of an ion therapy beam. The ionization chamber includes a chamber housing, a beam inlet window, a beam outlet window, a beam outlet window, and a chamber volume filled with counting gas.

H. Akiyama, et. al. "Charged-Particle Beam Irradiation Method and System", U.S. Pat. No. 6,433,349 (Aug. 13, 2002) and H. Akiyama, et. al. "Charged-Particle Beam Irradiation Method and System", U.S. Pat. No. 6,265,837 (Jul. 24, 2001) both describe a charged particle beam irradiation system that includes a changer for changing energy of the particle and an intensity controller for controlling an intensity of the charged-particle beam.

Y. Pu "Charged Particle Beam Irradiation Apparatus and Method of Irradiation with Charged Particle Beam", U.S. Pat. No. 6,034,377 (Mar. 7, 2000) describes a charged particle beam irradiation apparatus having an energy degrader comprising: (1) a cylindrical member having a length; and (2) a distribution of wall thickness in a circumferential direction around an axis of rotation, where thickness of the wall determines energy degradation of the irradiation beam.

Dosage

K. Matsuda, et. al. "Particle Beam Irradiation System", U.S. Pat. No. 7,372,053 (Nov. 27, 2007) describe a particle beam irradiation system ensuring a more uniform dose distribution at an irradiation object through use of a stop signal, which stops the output of the ion beam from the irradiation device.

H. Sakamoto, et. al. "Radiation Treatment Plan Making System and Method", U.S. Pat. No. 7,054,801 (May 30, 2006) describe a radiation exposure system that divides an exposure region into a plurality of exposure regions and uses a radiation simulation to plan radiation treatment conditions to obtain flat radiation exposure to the desired region.

G. Hartmann, et. al. "Method For Verifying the Calculated Radiation Dose of an Ion Beam Therapy System", U.S. Pat. No. 6,799,068 (Sep. 28, 2004) describe a method for the verification of the calculated dose of an ion beam therapy system that comprises a phantom and a discrepancy between the calculated radiation dose and the phantom.

H. Brand, et. al. "Method for Monitoring the Irradiation Control of an Ion Beam Therapy System", U.S. Pat. No. 6,614,038 (Sep. 2, 2003) describe a method of checking a calculated irradiation control unit of an ion beam therapy system, where scan data sets, control computer parameters, measuring sensor parameters, and desired current values of scanner magnets are permanently stored.

T. Kan, et. al. "Water Phantom Type Dose Distribution Determining Apparatus", U.S. Pat. No. 6,207,952 (Mar. 27, 2001) describe a water phantom type dose distribution apparatus that includes a closed water tank, filled with water to the brim, having an inserted sensor that is used to determine an actual dose distribution of radiation prior to radiation therapy.

Starting/Stopping Irradiation

K. Hiramoto, et. al. "Charged Particle Beam Apparatus and Method for Operating the Same", U.S. Pat. No. 6,316,776 (Nov. 13, 2001) describe a charged particle beam apparatus where a charged particle beam is positioned, started, stopped, and repositioned repetitively. Residual particles are used in the accelerator without supplying new particles if sufficient charge is available.

K. Matsuda, et. al. "Method and Apparatus for Controlling Circular Accelerator", U.S. Pat. No. 6,462,490 (Oct. 8, 2002) describe a control method and apparatus for a circular accelerator for adjusting timing of emitted charged particles. The clock pulse is suspended after delivery of a charged particle stream and is resumed on the basis of state of an object to be irradiated.

Movable Patient

N. Rigney, et. al. "Patient Alignment System with External Measurement and Object Coordination for Radiation Therapy System", U.S. Pat. No. 7,199,382 (Apr. 3, 2007) describe a patient alignment system for a radiation therapy system that includes multiple external measurement devices that obtain position measurements of movable components of the radiation therapy system. The alignment system uses the external measurements to provide corrective positioning feedback to more precisely register the patient to the radiation beam.

Y. Muramatsu, et. al. "Medical Particle Irradiation Apparatus", U.S. Pat. No. 7,030,396 (Apr. 18, 2006); Y. Muramatsu, et. al. "Medical Particle Irradiation Apparatus", U.S. Pat. No. 6,903,356 (Jun. 7, 2005); and Y. Muramatsu, et. al. "Medical Particle Irradiation Apparatus", U.S. Pat. No. 6,803,591 (Oct. 12, 2004) all describe a medical particle irradiation apparatus having a rotating gantry, an annular frame located within the gantry such that is can rotate relative to the rotating gantry, an anti-correlation mechanism to keep the frame from rotating with the gantry, and a flexible moving floor engaged with the frame is such a manner to move freely with a substantially level bottom while the gantry rotates.

H. Nonaka, et. al. "Rotating Radiation Chamber for Radiation Therapy", U.S. Pat. No. 5,993,373 (Nov. 30, 1999) describe a horizontal movable floor composed of a series of multiple plates that are connected in a free and flexible manner, where the movable floor is moved in synchrony with rotation of a radiation beam irradiation section.

Respiration

K. Matsuda "Radioactive Beam Irradiation Method and Apparatus Taking Movement of the Irradiation Area Into Consideration", U.S. Pat. No. 5,538,494 (Jul. 23, 1996) describes a method and apparatus that enables irradiation even in the case of a diseased part changing position due to physical activity, such as breathing and heart beat. Initially, a position change of a diseased body part and physical activity of the patient are measured concurrently and a relationship therebetween is defined as a function. Radiation therapy is performed in accordance to the function.

Patient Positioning

Y. Nagamine, et. al. "Patient Positioning Device and Patient Positioning Method", U.S. Pat. Nos. 7,212,609 and 7,212,608 (May 1, 2007) describe a patient positioning system that compares a comparison area of a reference X-ray image and a current X-ray image of a current patient location using pattern matching.

D. Miller, et. al. "Modular Patient Support System", U.S. Pat. No. 7,173,265 (Feb. 6, 2007) describe a radiation treatment system having a patient support system that includes a modularly expandable patient pod and at least one immobilization device, such as a moldable foam cradle.

K. Kato, et. al. "Multi-Leaf Collimator and Medical System Including Accelerator", U.S. Pat. No. 6,931,100 (Aug. 16, 2005); K. Kato, et. al. "Multi-Leaf Collimator and Medical System Including Accelerator", U.S. Pat. No. 6,823,045 (Nov. 23, 2004); K. Kato, et. al. "Multi-Leaf Collimator and Medical System Including Accelerator", U.S. Pat. No. 6,819,743 (Nov. 16, 2004); and K. Kato, et. al. "Multi-Leaf Collimator and Medical System Including Accelerator", U.S. Pat. No. 6,792,078 (Sep. 14, 2004) all describe a system of leaf plates used to shorten positioning time of a patient for irradiation therapy. Motor driving force is transmitted to a plurality of leaf plates at the same time through a pinion gear. The system also uses upper and lower air cylinders and upper and lower guides to position a patient.

Imaging

P. Adamee, et. al. "Charged Particle Beam Apparatus and Method for Operating the Same", U.S. Pat. No. 7,274,018 (Sep. 25, 2007) and P. Adamee, et. al. "Charged Particle Beam Apparatus and Method for Operating the Same", U.S. Pat. No. 7,045,781 (May 16, 2006) describe a charged particle beam apparatus configured for serial and/or parallel imaging of an object.

K. Hiramoto, et. al. "Ion Beam Therapy System and its Couch Positioning System", U.S. Pat. No. 7,193,2270 (Mar. 20, 2007) describe a ion beam therapy system having an X-ray imaging system moving in conjunction with a rotating gantry.

C. Maurer, et. al. "Apparatus and Method for Registration of Images to Physical Space Using a Weighted Combination of Points and Surfaces", U.S. Pat. No. 6,560,354 (May 6, 2003) described a process of X-ray computed tomography registered to physical measurements taken on the patient's body, where different body parts are given different weights. Weights are used in an iterative registration process to determine a rigid body transformation process, where the transformation function is used to assist surgical or stereotactic procedures.

M. Blair, et. al. "Proton Beam Digital Imaging System", U.S. Pat. No. 5,825,845 (Oct. 20, 1998) describe a proton beam digital imaging system having an X-ray source that is movable into the treatment beam line that can produce an X-ray beam through a region of the body. By comparison of the relative positions of the center of the beam in the patient orientation image and the isocentre in the master prescription image with respect to selected monuments, the amount and direction of movement of the patient to make the best beam center correspond to the target isocentre is determined.

S. Nishihara, et. al. "Therapeutic Apparatus", U.S. Pat. No. 5,039,867 (Aug. 13, 1991) describe a method and apparatus for positioning a therapeutic beam in which a first distance is determined on the basis of a first image, a second distance is determined on the basis of a second image, and the patient is moved to a therapy beam irradiation position on the basis of the first and second distances.

Problem

There exists in the art of particle beam therapy of cancerous tumors a need for positioning and verification of proper positioning of a patient immediately prior to and/or concurrently with particle beam therapy irradiation to ensure targeted and controlled delivery of energy to the cancerous tumor with minimization of damage to surrounding healthy tissue. There further exists a need for maintaining position of a patient throughout proton beam therapy treatment once positioning and verification of positioning of a patient is achieved.

SUMMARY OF THE INVENTION

The invention comprises a semi-vertical patient positioning and/or immobilization method and apparatus used in conjunction with charged particle beam radiation therapy of cancerous tumors.

DESCRIPTION OF THE FIGURES

FIG. **1** illustrates sub-system connections of a particle beam therapy system;

FIG. **2** illustrates a synchrotron;

FIG. **3** illustrates an X-ray source proximate a particle beam path;

FIG. **4** illustrates a semi-vertical patient positioning system;

FIG. **5** illustrates a back support;

FIG. **6** illustrates a knee support; and

FIG. **7** illustrates hand and head supports.

DETAILED DESCRIPTION OF THE INVENTION

The invention comprises a semi-vertical patient positioning and/or immobilization method and apparatus used in conjunction with charged particle beam radiation therapy of cancerous tumors.

Accurate and precise delivery of protons to a tumor in body tissue is critical in charged particle beam therapy. Complicating accurate and precise deliver is natural movement of the body. Movement of the body occurs on multiple levels, including: (1) general patient movement, such as walking; (2) standing, sitting, or lying position variation; and (3) relative movement of internal body parts, such as organs. All of these movements change with time. Hence, a method of determining position of elements of the body at and/or in close proximity in time to the charged particle therapy is needed, such as after the body is positioned relative to a charged particle beam. Herein, an X-ray positioning and/or verification method and apparatus used in conjunction with charged particle therapy is described. Further, a system for maintaining position of a patient throughout proton beam therapy treatment once positioning and verification of positioning of a patient is achieved is described.

The system controls movement of a patient during charged particle beam therapy, such as cancerous tumor treatment using proton beam therapy. A patient is positioned in a semi-vertical position in a proton beam therapy system. Patient positioning constraints are used to maintain the patient in a treatment position, including one or more of: a seat support, a back support, a head support, an arm support, a knee support, and a foot support. One or more of the positioning constraints are movable and/or under computer control for rapid positioning and/or immobilization of the patient. The system preferably uses an X-ray beam that lies in substantially the same path as a charged particle beam path of a particle beam cancer therapy system to align the subject just prior to proton beam therapy and/or to verify patient positioning during proton beam therapy. Since, the X-ray path is essentially the charged particle beam path, the generated X-ray image is usable for fine tuning body alignment relative to the charged particle beam path, is used to control the charged particle beam path to accurately and precisely target the tumor, and/or is used in system verification and validation.

Charged Particle Beam Therapy

Throughout this document, a charged particle beam therapy system, such as a proton beam, hydrogen ion beam, or carbon ion beam, is described. Herein, the charged particle beam therapy system is described using a proton beam. However, the aspects taught and described in terms of a proton beam are not intended to be limiting to that of a proton beam and are illustrative of a charged particle beam system. Any charged particle beam system is equally applicable to the techniques described herein.

Referring now to FIG. **1**, a charged particle beam system **100** is illustrated. A charged particle beam, preferably comprises a number of subsystems including any of: a main controller **110**; an injection system **120**; a synchrotron **130** that typically includes: (1) an accelerator system **132** and (2) an extraction system **134**; a targeting/delivery system **140**; a patient interface module **150**; a display system **160**; and/or an imaging system **170**.

An exemplary method of use of the charged particle beam system **100** is provided. The main controller **110** controls one or more of the subsystems to accurately and precisely deliver protons to a patient. For example, the main controller **110** obtains an image, such as a portion of a body and/or of a tumor, from the imaging system **170**. The main controller **110** also obtains position and/or timing information from the patient interface module **150**. The main controller **110** then optionally controls the injection system **120** to inject a proton into a synchrotron **130**. The synchrotron typically contains at least an accelerator system **132** and extraction system **134**. The main controller preferably controls the proton beam within the accelerator system, such as by controlling speed, trajectory, and timing of the proton beam. The main controller then controls extraction of a proton beam from the accelerator through the extraction system **134**. For example, the controller controls timing, energy, and intensity of the extracted beam. The controller **110** also preferably controls targeting of the proton beam through the targeting/delivery system **140** to the patient interface module **150**. One or more components of the patient interface module **150** are preferably controlled by the main controller **110**; Further, display elements of the display system **160** are preferably controlled via the main controller **110**; Displays are typically provided to one or more operators and/or to one or more patients. In one embodiment, the main controller **110** times the delivery of the proton beam from all systems, such that protons are delivered in an optimal therapeutic manner to the patient.

Herein, the main controller **110** refers to a single system controlling the charged particle beam system **100**, to a single controller controlling a plurality of subsystems controlling the charged particle beam system **100**, or to a plurality of individual controllers controlling one or more sub-systems of the charged particle beam system **100**.

Synchrotron

Herein, the term synchrotron is used to refer to a system maintaining the charged particle beam in a circulating path; however, cyclotrons are alternatively used, albeit with their inherent limitations of energy, intensity, and extraction control. Further, the charged particle beam is referred to herein as circulating along a circulating path about a central point of the synchrotron. The circulating path is alternatively referred to as an orbiting path; however, the orbiting path does not refer a perfect circle or ellipse, rather it refers to cycling of the protons around a central region.

Referring now to FIG. **2**, an illustrative exemplary embodiment of one version of the charged particle beam system **100** is provided. In the illustrated embodiment, a charged particle beam source **210** generates protons. The protons are delivered into a vacuum tube that runs into, through, and out of the synchrotron. The generated protons are delivered along an initial path **220**. Focusing magnets **230**, such as quadrupole magnets or injection quadrupole magnets, are used to focus the proton beam path. A quadrupole magnet is a focusing magnet. An injector bending magnet **232** bends the proton beam toward the plane of the synchrotron **130**. The focused protons having an initial energy are introduced into an injector magnet **240**, which is preferably an injection Lamberson magnet. Typically, the initial beam path **262** is along an axis off of, such as above, a circulating plane of the synchrotron **130**. The injector bending magnet **232** and injector magnet **240** combine to move the protons into the synchrotron **130**. Circulating magnets or main bending magnets **250** are used to turn the protons along a circulating beam path **260**. The circulating magnets **250** bend the original beam path **220** into a circulating beam path **260**. In this example, the circulating magnets **250** are represented as four sets of four magnets to maintain the circulating beam path **260** into a stable circulating beam path. A plurality of main bending magnets make up a turning section of the synchrotron. In the illustrated exemplary embodiment, four main bending magnets make up a turning section turning the proton beam about ninety degrees. Optionally, any number of magnets or sets of magnets are optionally used to move the protons around a single orbit in the circulation process. The protons pass through an accelerator **270**. The accelerator accelerates the protons in the beam path **260**. As the protons are accelerated, the fields applied by the magnets are increased. Particularly, the speed of the protons achieved by the accelerator **270** are synchronized with magnetic fields of the circulating magnets **250** to maintain stable circulation of the protons about a central point or region **280** of the synchrotron. At separate points in time the accelerator **270**/circulating magnet **250** combination is used to accelerate and/or decelerate the circulating protons. An extraction system **290** is used in combination with a deflector **300** to remove protons from their circulating path **260** within the synchrotron **190**. One example of a deflector component is a Lamberson magnet. Typically the deflector moves the protons from the circulating plane to an axis off of the circulating plane, such as above the circulating plane. Extracted protons are preferably directed and/or focused using an extraction bending magnet **237** and extraction focusing magnets **235**, such as quadrupole magnets along a transport path into the scanning/targeting/delivery system **160**. Two components of a targeting system **160** typically include a first axis control **162**, such as a vertical control, and a second axis control **164**, such as a horizontal control. Protons are delivered with control to the patient interface module **170** and to a tumor of a patient. Preferably no quadrupoles are used in or around the circulating path of the synchrotron.

Proton Beam Extraction

Generally, protons are extracted from the synchrotron by slowing the protons. As described, supra, the protons were initially accelerated in a circulating path, which is maintained with a plurality of turning magnets. The circulating path is referred to herein as an original central beamline. The protons repeatedly cycle around a central point in the synchrotron. The proton path traverses through an RF cavity system. To initiate extraction, an RF field is applied across a first blade and a second blade, in the RF cavity system. The first blade and second blade are referred to herein as a first pair of blades.

In the proton extraction process, a radio-frequency (RF) voltage is applied across the first pair of blades, where the first blade of the first pair of blades is on one side of the circulating proton beam path and the second blade of the first pair of blades is on an opposite side of the circulating proton beam path. The applied RF field applies energy to the circulating charged-particle beam. The applied RF field alters the orbiting or circulating beam path slightly of the protons from the original central beamline to an altered circulating beam path. Upon a second pass of the protons through the RF cavity system, the RF field further moves the protons off of the original proton beamline. For example, if the original beamline is considered as a circular path, then the altered beamline is slightly elliptical. The applied RF field is timed to apply outward or inward movement to a given band of protons circulating in the synchrotron accelerator. Each orbit of the protons is slightly more off axis compared to the original circulating beam path. Successive passes of the protons through the RF cavity system are forced further and further from the original central beamline by altering the direction and/or intensity of the RF field with each successive pass of the proton beam through the RF field.

The RF voltage is frequency modulated at a frequency about equal to the period of one proton cycling around the synchrotron for one revolution or at a frequency than is an integral multiplier of the period of one proton cycling about the synchrotron. The applied RF frequency modulated voltage excites a betatron oscillation. For example, the oscillation is a sine wave motion of the protons. The process of timing the RF field to a given proton beam within the RF cavity system is repeated thousands of times with each successive pass of the protons being moved approximately one micrometer further off of the original central beamline. For clarity, the effect of the approximately changing beam paths with each successive path of a given band of protons through the RF field is illustrated as the altered beam path.

With a sufficient sine wave betatron amplitude, the altered circulating beam path touches a material, such as a foil or a sheet of foil. The foil is preferably a lightweight material, such as beryllium, a lithium hydride, a carbon sheet, or a material of low nuclear charge. A material of low nuclear charge is a material composed of atoms consisting essentially of atoms having six or fewer protons. The foil is preferably about 10 to 150 microns thick, is more preferably 30 to 100 microns thick, and is still more preferably 40-60 microns thick. In one example, the foil is beryllium with a thickness of about 50 microns. When the protons traverse through the foil, energy of the protons is lost and the speed of the protons is reduced. Typically, a current is also generated, described infra. Protons moving at a slower speed travel in the synchrotron with a reduced radius of curvature compared to either the original central beamline or the altered circulating path. The reduced radius of curvature path is also referred to herein as a path having a smaller diameter of trajectory or a path having protons with reduced energy. The reduced radius of curvature is typically about two millimeters less than a radius of curvature of the last pass of the protons along the altered proton beam path.

The thickness of the material **1230** is optionally adjusted to create a change in the radius of curvature, such as about ½, 1, 2, 3, or 4 mm less than the last pass of the protons or original radius of curvature. Protons moving with the smaller radius of curvature travel between a second pair of blades. In one case, the second pair of blades is physically distinct and/or are separated from the first pair of blades. In a second case, one of the first pair of blades is also a member of the second pair of blades. For example, the second pair of blades is the second blade and a third blade in the RF cavity system. A high voltage DC signal, such as about 1 to 5 kV, is then applied across the second pair of blades, which directs the protons out of the synchrotron through a deflector, such as a Lamberson magnet, into a transport path.

Control of acceleration of the charged particle beam path in the synchrotron with the accelerator and/or applied fields of the turning magnets in combination with the above described extraction system allows for control of the intensity of the extracted proton beam, where intensity is a proton flux per unit time or the number of protons extracted as a function of time. For example, when a current is measured beyond a threshold, the RF field modulation in the RF cavity system is terminated or reinitiated to establish a subsequent cycle of proton beam extraction. This process is repeated to yield many cycles of proton beam extraction from the synchrotron accelerator.

Because the extraction system does not depend on any change any change in magnetic field properties, it allows the synchrotron to continue to operate in acceleration or deceleration mode during the extraction process. Stated differently, the extraction process does not interfere with synchrotron. In stark contrast, traditional extraction systems introduce a new magnetic field, such as via a hexapole, during the extraction process. More particularly, traditional synchrotrons have a magnet, such as a hexapole magnet, that is off during an acceleration stage. During the extraction phase, the hexapole magnetic field is introduced to the circulating path of the synchrotron. The introduction of the magnetic field necessitates two distinct modes, an acceleration mode and an extraction mode, which are mutually exclusive in time.

In one example, the charged particle irradiation includes a synchrotron having: a center, straight sections, and turning sections. The charged particle beam path runs about the center, through the straight sections, and through said turning sections, where each of the turning sections comprises a plurality of bending magnets. Preferably, the circulation beam path comprises a length of less than sixty meters, and the number of straight sections equals the number of turning sections.

Imaging System

Herein, an X-ray system is used to illustrate an imaging system.

Timing

An X-ray is preferably collected either (1) just before or (2) concurrently with treating a subject with proton therapy for a couple of reasons.

First, movement of the body, described supra, changes the local position of the tumor in the body. If the subject has an X-ray taken and is then bodily moved to a proton treatment room, accurate alignment of the proton beam to the tumor is problematic. Alignment of the proton beam to the tumor using one or more X-rays is best performed at the time of proton delivery or in the seconds or minutes immediately prior to proton delivery and after the patient is placed into a therapeutic body position, which is typically a fixed position.

Second, the X-ray taken after positioning the patient is used for verification of proton beam alignment to a targeted position, such as a tumor and/or internal organ position.

Positioning

An X-ray is preferably taken just before treating the subject to aid in patient positioning. For positioning purposes, an X-ray of a large body area is not needed. In one embodiment, an X-ray of only a local area is collected. When collecting an X-ray, the X-ray has an X-ray path. The proton beam has a proton beam path. Overlaying the X-ray path with the proton beam path is one method of aligning the proton beam to the tumor. However, this method involves putting the X-ray equipment into the proton beam path, taking the X-ray, and then moving the X-ray equipment out of the beam path. This process takes time. The elapsed time while the X-ray equipment moves has a couple of detrimental effects. First, during the time required to move the X-ray equipment, the body moves. The resulting movement decreases precision and accuracy of subsequent proton beam alignment to the tumor. Second, the time require to move the X-ray equipment is time that the proton beam therapy system is not in use, which decreases the total efficiency of the proton beam therapy system.

Referring now to FIG. **3**, in one embodiment, an X-ray is generated close to, but not in, the proton beam path. A proton beam therapy system and an X-ray system combination **300** is illustrated in FIG. **3**. The proton beam therapy system has a proton beam **260** in a transport system after the deflector **292** of the synchrotron **130**. The proton beam is directed by the targeting/delivery system **140** to a tumor **320** of a patient **330**. The X-ray system **305** includes an electron beam source **340** generating an electron beam **350**. The electron beam is directed to an X-ray generation source **360**, such as a piece of tungsten. Preferably, the tungsten X-ray source is located about 1, 2, 3, 5, 10, or 20 millimeters from the proton beam path **260**. When the electron beam **350** hits the tungsten, X-rays are generated in all directions. X-rays are blocked with a port **362** and are selected for an X-ray beam path **370**. The X-ray beam path **370** and proton beam path **260** run substantially in parallel to the tumor **320**. The distance between the X-ray beam path **370** and proton beam path diminishes to near zero and/or the X-ray beam path **370** and proton beam path **269** overlap by the time they reach the tumor **320**. Simple geometry shows this to be the case given the long distance, of at least a meter, between the tungsten and the tumor **320**. The distance is illustrated as a gap **380** in FIG. **3**. The X-rays are detected at an X-ray detector **390**, which is used to form an image of the tumor **320** and/or position of the patient **330**.

As a whole, the system generates an X-ray beam that lies in substantially the same path as the proton therapy beam. The X-ray beam is generated by striking a tungsten or equivalent material with an electron beam. The X-ray generation source is located proximate to the proton beam path. Geometry of the incident electrons, geometry of the X-ray generation material, and geometry of the X-ray beam blocker **262** yield an X-ray beam that runs either in substantially in parallel with the proton beam or results in an X-ray beam path that starts proximate the proton beam path an expands to cover and transmit through a tumor cross-sectional area to strike an X-ray detector array or film allowing imaging of the tumor from a direction and alignment of the proton therapy beam. The X-ray image is then used to control the charged particle beam path to accurately and precisely target the tumor, and/or is used in system verification and validation.

Vertical Patient Positioning/Immobilization

In this section an x-, y-, and z-axes coordinate system and rotation axis is used to describe the orientation of the patient relative to the proton beam. The z-axis represent travel of the proton beam, such as the depth of the proton beam into the patient. When looking at the patient down the z-axis of travel of the proton beam, the x-axis refers to moving left or right across the patient and the y-axis refers to movement up or down the patient. The y-axis is aligned with gravity. A first rotation axis is rotation of the patient about the y-axis and is referred to herein as a rotation axis or y-axis of rotation.

In one example, an X-ray generation source is located within about forty millimeters of the charged particle beam path, where the X-ray source maintains a single static position: (1) during use of the X-ray source and (2) during tumor treatment with the charged particles. In this example, the X-ray generation source is a tungsten anode and X-rays emitted from the X-ray source run substantially in parallel with the charged particle beam path. Preferably, use of said X-ray generation source occurs within thirty seconds of subsequent use of the charged particle irradiation system.

In another example, the charged particle irradiation system includes horizontal position control of the charged particles, vertical position control of the charged particles, and an X-ray input signal, where the X-ray input signal includes a signal generated by an X-ray source proximate the charged particle beam path. Preferably, the X-ray input signal is used in: setting position of the horizontal position and setting position of the vertical position of the charged particle beam path.

Referring now to FIG. **4**, a semi-vertical patient positioning and/or immobilization system **400** is described. The patient positioning and/or immobilization system **400** controls movement of the patient during proton beam therapy. The patient is positioned in a semi-vertical position in a proton beam therapy system. As illustrated, the patient is reclining at an angle alpha, α, about 45 degrees off of the y-axis as defined by an axis running from head to foot of the patient. More generally, the patient is optionally completely standing in a vertical position of zero degrees off the of y-axis or is in a semi-vertical position alpha that is reclined about 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, or 55 degrees off of the y-axis. In one example, the patient positioning system includes an upper body support, where the upper body support includes a semi-upright patient support surface. Preferably, the charged particle irradiation system includes a charged particle beam path and the charged particle beam path passes within about six inches of the semi-upright patient support surface.

Still referring to FIG. **4**, patient positioning constraints **415** are used to maintain the patient in a treatment position, including one or more of: a seat support **420**, a back support **430**, a head support **440**, an arm support **450**, a knee support **460**, and a foot support **470**. The constraints are optionally and independently rigid or semi-rigid. Examples of semi-rigid material include a high or low density foam or a visco-elastic foam. For example the foot support **470** is preferably rigid and the back support **430** is preferably semi-rigid, such as a high density foam material. One or more of the positioning constraints **415** are movable and/or under computer control for rapid positioning and/or immobilization of the patient. For example, the seat support **420** is adjustable along a seat adjustment axis **422**, which is preferably the y-axis; the back support **430** is adjustable along a back support axis **432**, which is preferably dominated by z-axis movement with a y-axis element; the head support **440** is adjustable along a head support axis **442**, which is preferably dominated by z-axis movement with a y-axis element; the arm support **450** is adjustable along an arm support axis, which is preferably dominated by z-axis movement with a y-axis element; the knee support **460** is adjustable along a knee support axis **462**, which is preferably dominated by y-axis movement with a z-axis element; and the foot support **470** is adjustable along a foot support axis, which is preferably dominated by y-axis movement with a z-axis element. In one example, the patient positioning system reduces movement freedom of the tumor in terms of any of: horizontal movement, vertical movement, movement in parallel to said charged particle beam path above a portion of said patient positioning system, yaw, pitch, and roll.

Still referring to FIG. **4**, the patient is preferably positioned on a patient positioning unit **410**, which optionally includes a bottom unit **412** and a top unit **414**. Preferably, some of the patient positioning constraints **415** are fixed to and supported by the patient positioning unit **410**. For instance, some of the patient positioning constraints **415** are fixed to and supported by the bottom unit **412** and some of the patient positioning constraints **415** are fixed to and supported by the top unit **414**. Additionally, preferably the patient positioning unit **410** is adjustable along the y-axis **416** to allow vertical positioning of the patient relative to the proton therapy beam **260**. Additionally, preferably the patient positioning unit **410** is rotatable about a rotation axis **417**, such as about the y-axis, to allow rotational control and positioning of the patient relative to the proton beam path **260**. The rotation of the positioning unit is illustrated about the rotation axis **417** at three distinct times, t_1, t_2, and t_3.

Still referring to FIG. **4**, an optional camera **480** is illustrated. The camera views the subject **330** creating an video image. The image is provided to one or more operators of the charged particle beam system and allows the operators one safety mechanism for determining if the subject has moved or desires to terminate the proton therapy treatment procedure. Based on the video image, the operators may suspend or terminate the proton therapy procedure.

Still referring to FIG. **4**, an optional video display **490** is provided to the patient. The video display optionally presents to the patient any of: operator instructions, system instructions, status of treatment, or entertainment.

Breath control is optionally performed by using the video display **490**. As the patient breathes, internal and external structures of the body move in both absolute terms and in relative terms. For example, the outside of the chest cavity and internal organs both have absolute moves with a breath. In addition, the relative position of an internal organ relative to another body component, such as an outer region of the body, a bone, support structure, or another organ, moves with each breath. Hence, for more accurate and precise tumor targeting, the proton beam is preferably delivered at point a in time where the position of the internal structure or tumor is well defined, such as at the bottom of each breath. The video display **490** is used to help coordinate the proton beam delivery with the patient's breathing cycle. For example, the video display **490** optionally displays to the patient a command, such as a hold breath statement, a breath statement, a countdown indicating when a breadth will next need to be held, or a countdown until breathing may resume.

Referring now to FIG. **5**, an example of the back support **430** is further described. Referring to FIG. **5**, an example of a perspective orientation of the back support **430** is illustrated. The back support is preferably curved to support the patient's back and to wrap onto the sides of the patient's torso. The back support preferably has two semi-rigid portions, a left side **510** and right side **520**.

Further, the back support **430** has a top end **530** and a bottom end **540**. A first distance **550** between the top ends **530** of the left side **510** and right side **520** is preferably adjustable to fit the upper portion of the patient's back. A second distance **560** between the bottom ends **540** of the left side **510** and right side **520** is preferably independently adjustable to fit the lower portion of the patient's back.

Referring now to FIG. **6**, an example of the knee support **460** is further described. The knee support preferably has a left knee support **610** and a right knee support **620** that are optionally connected or individually movable. Both the left and right knee supports **610**, **620** are preferably curved to fit standard sized knees **332**. The left knee support **610** is optionally adjustable along a left knee support axis **612** and the right knee support **620** is optionally adjustable along a right knee support axis **622**. Alternatively, the left and right knee supports **610**, **620** are connected and movable along the knee support axis **462**. Both the left and right knee supports **610**, **620**, like the other patient positioning constraints **415**, are preferably made of a semi-rigid material, such as a low or high density foam, having an optional covering, such as a plastic or leather.

Referring now to FIG. **7**, an example of the head support **440** is further described. The head support **440** is preferably curved to fit a standard or child sized head **336**. The head support **440** is optionally adjustable along a head support axis **442**. Further, the head supports **440**, like the other patient positioning constraints **415**, is preferably made of a semi-rigid material, such as a low or high density foam, and has an optional covering, such as a plastic or leather.

Still referring to FIG. **7**, an example of the arm support **450** is further described. The arm support preferably has a left hand grip **710** and a right hand grip **720** used for aligning the upper body of the patient **330** through the action of the patient **330** gripping the left and right hand grips **710**, **720** with the patient's hands **334**. The left and right hand grips **710**, **720** are preferably connected to the arm support **450** that supports the mass of the patient's arms. The left and right hand grips **710**, **720** are preferably constructed using a semi-rigid material. The left and right hand grips **710**, **720** are optionally molded to the patient's hands to aid in alignment.

Positioning System Computer Control

One or more of the patient positioning unit **410** components and/or one of more of the patient positioning constraints **415** are preferably under computer control, where the computer control positioning devices, such as via a series of motors and drives, to reproducibly position the patient. For example, the patient is initially positioned and constrained by the patient positioning constraints **415**. The position of each of the patient positioning constraints **415** is recorded and saved by the main controller **110**, by a sub-controller or the main controller **110**, or by a separate computer controller. Then, medical devices are used to locate the tumor **320** in the patient **330** while the patient is in the orientation of final treatment. The imaging system **170** includes one or more of: MRI's, X-rays, CT's, proton beam tomography, and the like. Time optionally passes at this point where images from the imaging system **170** are analyzed and a proton therapy treatment plan is devised. The patient may exit the constraint system during this time period, which may be minutes, hours, or days. Upon return of the patient to the patient positioning unit **410**, the computer can return the patient positioning constraints **415** to the recorded positions. This system allows for rapid repositioning of the patient to the position used during imaging and development of the treatment plan, which minimizes setup time of patient positioning and maximizes time that the charged particle beam system **100** is used for cancer treatment

Proton Beam Therapy Synchronization with Breathing

In another embodiment, delivery of a proton beam dosage is synchronized with a breathing pattern of a subject. When a subject, also referred to herein as a patient, is breathing many portions of the body move with each breath. For example, when a subject breathes the lungs move as do relative positions of organs within the body, such as the stomach, kidneys, liver, chest muscles, skin, heart, and lungs. Generally, most or all parts of the torso move with each breath. Indeed, the inventors have recognized that in addition to motion of the torso with each breath, various motion also exists in the head and limbs with each breath. Motion is to be considered in delivery of a proton dose to the body as the protons are preferentially delivered to the tumor and not to surrounding tissue. Motion thus results in an ambiguity in where the tumor resides relative to the beam path. To partially overcome this concern, protons are preferentially delivered at the same point in a breathing cycle.

Initially a rhythmic pattern of breathing of a subject is determined. The cycle is observed or measured. For example, a proton beam operator can observe when a subject is breathing or is between breaths and can time the delivery of the protons to a given period of each breath. Alternatively, the subject is told to inhale, exhale, and/or hold their breath and the protons are delivered during the commanded time period. Preferably, one or more sensors are used to determine the breathing cycle of the individual. For example, a breath monitoring sensor senses air flow by or through the mouth or nose. Another optional sensor is a chest motion sensor attached or affixed to a torso of the subject.

Once the rhythmic pattern of the subject's breathing is determined, a signal is optionally delivered to the subject to more precisely control the breathing frequency. For example, a display screen is placed in front of the subject directing the subject when to hold their breath and when to breath. Typically, a breathing control module uses input from one or more of the breathing sensors. For example, the input is used to determine when the next breath exhale is to complete. At the bottom of the breath, the control module displays a hold breath signal to the subject, such as on a monitor, via an oral signal, digitized and automatically generated voice command, or via a visual control signal. Preferably, a display monitor is positioned in front of the subject and the display monitor displays at least breathing commands to the subject. Typically, the subject is directed to hold their breath for a short period of time, such as about one-half, one, two, or three seconds. The period of time the subject is asked to hold their breath is less than about ten seconds as the period of time the breath is held is synchronized to the delivery time of the proton beam to the tumor, which is about one-half, one, two, or three seconds. While delivery of the protons at the bottom of the breath is preferred, protons are optionally delivered at any point in the breathing cycle, such as upon full inhalation. Delivery at the top of the breath or when the patient is directed to inhale deeply and hold their breath by the breathing control module is optionally performed as at the top of the breath the chest cavity is largest and for some tumors the distance between the tumor and surrounding tissue is maximized or the surrounding tissue is rarefied as a result of the increased volume. Hence, protons hitting surrounding tissue is minimized. Optionally, the display screen tells the subject when they are about to be asked to hold their breath, such as with a 3, 2, 1, second countdown so that the subject is aware of the task they are about to be asked to perform.

A proton delivery control algorithm is used to synchronize delivery of the protons to the tumor within a given period of each breath, such as at the bottom of a breath when the subject is holding their breath. The proton delivery control algorithm is preferably integrated with the breathing control module. Thus, the proton delivery control algorithm knows when the subject is breathing, where in the breath cycle the subject is, and/or when the subject is holding their breath. The proton delivery control algorithm controls when protons are injected and/or inflected into the synchrotron, when an RF signal is applied to induce an oscillation, as described supra, and when a DC voltage is applied to extract protons from the synchrotron, as described supra. Typically, the proton delivery control algorithm initiates proton inflection and subsequent RF induced oscillation before the subject is directed to hold their breath or before the identified period of the breathing cycle selected for a proton delivery time. In this manner, the proton delivery control algorithm can deliver protons at a selected period of the breathing cycle by simultaneously or near simultaneously delivering the high DC voltage to the second pair of plates, described supra, that results in extraction of the protons from the synchrotron and subsequent delivery to the subject at the selected time point. Since the period of acceleration of protons in the synchrotron is constant, the proton delivery control algorithm is used to set an AC RF signal that matches the breathing cycle or directed breathing cycle of the subject.

In yet another example, the patient is held on the rotatable platform, where the rotatable platform holds at least a portion of the patient positioning system. The patient is preferably rotated on the rotatable platform and the charged particles are delivered to the tumor of the patient from a synchrotron of the charged particle system during or interspersed with the step of rotating the patient. Optionally, a respiration signal is generated with a respiration sensor, where the respiration signal corresponds to a breathing cycle of the patient and delivery of the charged particles to the tumor is timed to a set point in said breathing cycle using the respiration signal. Preferably, the charged particles are independently controlled in terms of: a horizontal position of the charged particles and a vertical position of the charged particles. Preferably, the patient is rotated to at least ten rotation positions of the rotatable platform during charged particle therapy where the rotatable platform rotates through at least one hundred eighty degrees and preferably through three hundred sixty degrees during an irradiation period of the patient.

Although the invention has been described herein with reference to certain preferred embodiments, one skilled in the art will readily appreciate that other applications may be substituted for those set forth herein without departing from the spirit and scope of the present invention. Accordingly, the invention should only be limited by the Claims included below.

The invention claimed is:

1. An apparatus for positioning a tumor of a patient for treatment with positively charged particles, comprising:
- a patient positioning system, comprising:
  - a rotatable platform configured to both support and rotate the patient during use;
  - an upper body support affixed to said rotatable platform, wherein said upper body support comprises:
    - a semi-upright patient support surface; and
    - a motorized head positioning system;
  - an upper support structure, said upper support structure configured to:
    - co-rotate with said rotatable platform;
    - hold a camera, both (1) said camera and (2) said upper support structure configured to rotate about an axis aligned with gravity during use; and
    - hold a video display screen, said video display screen configured to co-rotate, about the axis aligned with gravity, with said upper support structure in view of a patient viewing position;
  - means for recalling patient specific motor positions for: said motorized head positioning system; and
- a charged particle irradiation system comprising a charged particle beam path, said charged particle beam path passing within about six inches of said semi-upright patient support surface.

2. The apparatus of claim **1**, wherein said charged particle beam path passes above a portion of said rotatable platform.

3. The apparatus of claim **2**, wherein said rotatable platform further comprises:
- a lower support structure, said lower support structure holding a portion of said patient positioning system, said lower support structure indirectly supporting a back support, said back support comprising:
  - a left side portion;
  - a right side portion,
  - a first distance between an upper end of said left side portion and an upper end of said right side portion; and
  - a second distance between a lower end of said left side portion and a lower end of said right side portion, said first distance and said second distance comprising independently adjustable distances.

4. The apparatus of claim **1**, further comprising:
- an X-ray generation source located within forty millimeters of the charged particle beam path, wherein said X-ray source maintains a single static position: (1) during use of said X-ray source and (2) during tumor treatment with the positively charged particles,
- wherein X-rays emitted from said X-ray source run substantially in parallel with the charged particle beam path.

5. The apparatus of claim **4**, wherein said X-ray generation source comprises a tungsten anode.

6. The apparatus of claim **4**, wherein use of said X-ray generation source occurs within thirty seconds of subsequent use of said charged particle irradiation system.

7. The apparatus of claim **1**, wherein the positively charged particles travel along said charged particle beam path to the tumor of the patient.

8. The apparatus of claim **1**, wherein said semi-upright patient support surface comprises an about vertical surface.

9. The apparatus of claim **1**, wherein said semi-upright patient support surface is reclined from a vertical axis by less than about sixty-five degrees.

10. The apparatus of claim **1**, wherein said patient positioning system further comprises:

a motorized foot positioning system configured to adjust an angle of a foot of the patient independently of an angle of a torso of the patient.

11. The apparatus of claim **1**, further comprising:

means for recalling a historical position of the patient after the patient has departed from the apparatus for a period of at least hours.

12. The apparatus of claim **1**, wherein said patient positioning system provides respiration instructions on said video screen, said respiration instructions generated using a respiration sensor configured to monitor the patient during use, said video screen configured to co-rotate with the patient about the axis aligned with gravity during use.

13. The apparatus of claim **1**, wherein said patient positioning system reduces movement freedom of the tumor in terms of roll.

14. The apparatus of claim **1**, said charged particle irradiation system further comprising a synchrotron, said synchrotron comprising:

a center;

straight sections;

turning sections; and

an extraction system comprising an extraction foil proximate the charged particle beam path, wherein said extraction system applies a radio-frequency field to the positively charged particles during use to alter the charged particle beam path through the extraction foil, said extraction foil positioned in the charged particle beam path prior to at least one Lambertson magnet about the charged particle beam path,

wherein said charged particle beam path runs;

about said center;

through said straight sections; and

through said turning sections,

wherein each of said turning sections comprises a plurality of bending magnets,

wherein said circulation beam path comprises a length of less than sixty meters, and

wherein a number of said straight sections equals a number of said turning sections.

15. The apparatus of claim **1**, wherein said charged particle irradiation system further comprises:

horizontal position control of the positively charged particles;

vertical position control of the positively charged particles; and

an X-ray input signal, wherein said X-ray input signal comprises a signal generated by an X-ray source proximate said charged particle beam path,

wherein said X-ray input signal is used in: setting position of said horizontal position and setting position of said vertical position.

16. A method for positioning a tumor of a patient for treatment with positively charged particles, comprising the steps of:

positioning the patient with a patient positioning system, said patient positioning system comprising:

a rotatable platform, wherein said rotatable platform comprises:

a lower support structure, said lower support structure holding a portion of said patient positioning system;

a rotatable upper support structure, said upper support structure:

co-rotating with said rotatable platform;

holding a camera, both (1) said camera and (2) said upper support structure co-rotating about an axis aligned with gravity; and

holding a video display screen, said video screen co-rotating, about the axis aligned with gravity, with said upper support structure in view of a patient viewing position;

an upper body support, wherein said upper body support comprises a semi-upright patient support surface; and

irradiating the tumor of the patient with the positively charged particles from a charged particle system, said charged particle system comprising a charged particle beam path, said charge particle beam path passing within about six inches of said semi-upright patient support surface.

17. The method of claim **16**, wherein the positively charged particles travel along said charged particle beam path and transmit through an extraction blade, said extraction blade consisting essentially of atoms comprising six or fewer protons per atom, to the tumor of the patient.

18. The method of claim **16**, wherein said semi-upright patient support surface comprises an about vertical surface.

19. The method of claim **16**, wherein said semi-upright patient support surface comprises a reclined position from a vertical axis of less than about sixty-five degrees.

20. The method of claim **16**, further comprising the step of:

said patient positioning system semi-restraining movement of the patient using

a motorized arm positioning system, said motorized arm positioning system directly connected to said rotatable upper support structure.

21. The method of claim **16**, further comprising the step of:

when the patient returns to the patient positioning system after a period of at least hours, recalling from a computer memory patient specific motor positions for any of:

said motorized head positioning system;

said motorized arm positioning system; and

said motorized foot positioning system.

22. The method of claim **16**, further comprising the steps of:

after said step of positioning, collecting multi-field images of the tumor in the patient;

developing a tumor irradiation plan;

at least one day after said step of positioning, repositioning the tumor using said patient positioning system using any of the patient specific motor positions stored in said computer memory; and

repeating said step of irradiating.

23. The method of claim **16**, further comprising the steps of:

holding the patient with a rotatable platform, said rotatable platform holding at least a portion of said patient positioning system;

rotating the patient on said rotatable platform; and

delivering the positively charged particles to the tumor of the patient from a synchrotron of said charged particle system during said step of rotating the patient.

24. The method of claim **16**, further comprising the steps of:

generating a respiration signal with a respiration sensor, said respiration signal corresponding to a breathing cycle of the patient;

using data from the respiration sensor in a step of delivering a computer generated command to the patient; and

timing delivery of the positively charged particles to the tumor at a set point in said breathing cycle using said respiration signal.

25. The method of claim **16**, further comprising the steps of:

independently controlling:

  a horizontal position of the positively charged particles; and

  a vertical position of the positively charged particles;

rotating the patient to at least ten rotation positions of a rotatable platform, said rotatable platform holding at least a portion of said patient positioning system; and

delivering the positively charged particles at a set point in a breathing cycle of the patient and in coordination with said step of rotating during said at least ten rotation positions of said rotatable platform.

26. The method of claim **16**, further comprising the step of:

rotating a rotatable platform through at least one hundred eighty degrees during an irradiation period of the patient, said rotatable platform holding at least a portion of said patient positioning system.

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